Annual Project Summary Report for 10/01/03 - 9/30/04

Probabilistic Residual Shear Strength Criteria for Post-Liquefaction Evaluation of Cohesionless Soil Deposits

USGS Grant Award No. 04HQGR0076

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Keywords: Geotechnical, Liquefaction, Probabilistic Seismic Hazards

NON-TECHNICAL SUMMARY

Liquefaction is the phenomena where cohesionless soils lose strength as a result of earthquake shaking, static loads, or deformations. Over the past 40 years, geologists and engineers have documented failures where liquefaction was the apparent culprit. Researchers have made attempts to determine the strength of susceptible material before and after liquefaction has occurred based on these case histories. However, the analyses have not directly accounted for the variability of material properties. The main objectives of this research project are to quantify uncertainties associated with the various case histories and provide procedures for analyzing liquefiable soil deposits within a risk-based framework.

INVESTIGATIONS UNDERTAKEN

This research project aims to quantify uncertainties associated with the yield and post-liquefaction residual shear strength of cohesionless soil deposits. The primary goal of this research was to develop robust, reliability-based procedures for determining the yield and liquefied shear strength of cohesionless soils based on the back analysis of historical flow liquefaction and lateral spreading failures. These failures have been obtained from existing databases and additional cases have been sought out from the available literature to create two comprehensive databases. The back analyses are performed using reliability-based spreadsheets developed for several slope stability models including Ishihara's simplified slope stability analysis (Ishihara et al., 1990) and Spencer's generalized method of slices (Spencer, 1973) for flow liquefaction failures, and Newmark's sliding block model for lateral spreading failures (Newmark, 1965). Results from these analyses should provide insight into two controversial questions:

1. Should the yield and liquefied shear strengths be normalized by the initial effective vertical stress?
2. Should flow liquefaction and lateral spreading case histories be included in the same database for developing relationships between yield and liquefied shear strengths with insitu testing parameters?

After the databases of flow liquefaction and lateral spreading failures have been analyzed, the yield and liquefied shear strengths will be statistically mapped to insitu test results with logistical regression and Bayesian theory (Juang et al., 2002). Recommendations and spreadsheets will be provided so that the results of this research are easily implemented into practice.

RESULTS

During the report period of October 1, 2003 - September 30, 2004 the following tasks have been accomplished:

1. Review of available literature regarding liquefaction of cohesionless soil deposits and the application of various reliability techniques to slope stability analysis.
2. Collection of information regarding existing and additional case histories of flow liquefaction and lateral spreading.
3. Development of a Spencer's generalized method of slices spreadsheet to analyze the cases of flow liquefaction within a reliability framework.
4. Reliability-based back analysis of several flow liquefaction case histories using spreadsheet to estimate yield shear strengths of cohesionless soil deposits.

The following sections provide discussion regarding the list of accomplished tasks. The first section describes the reliability procedures adopted for quantifying the uncertainties involved in the various case histories. The second section presents the case histories of flow liquefaction and lateral spreading that constitute two new comprehensive databases. The third section discusses the Spencer's spreadsheet developed to study the flow liquefaction case histories. The final section presents results from back-analysis of the Fort Peck Dam flow liquefaction failure.

Reliability Procedures

The reliability of the each case history is measured with the Hasofer-Lind reliability index, β (Hasofer and Lind, 1974). Various techniques are described in the literature to evaluate β, typically involving some type of iterative numerical procedure to obtain an answer. This research adopts a convenient spreadsheet approach proposed by Low and Tang (2004), where object-oriented constrained optimization is used to obtain a solution for β with equation (1):

$$\beta = \min_{\underline{x}\in F} \sqrt{\left[\frac{x_i - m_i^N}{\sigma_i^N}\right]^{\mathrm{T}} \left[\underline{R}\right]^{-1} \left[\frac{x_i - m_i^N}{\sigma_i^N}\right]} \tag{1}$$

where $\underline{x}$ is a vector representing the random variables, F is the failure domain, $\underline{R}$ is the correlation matrix, and m_i^N and σ_i^N are the mean and standard deviation computed from Rackwitz-Fiessler (1978) two-parameter equivalent normal transformations. By using the equivalent normal parameters, model properties with different probability distributions (i.e. normal, lognormal, uniform, beta, etc.) can easily be used in the same analysis. The probability distribution parameters are determined through statistical analysis when data are available. For those cased histories where site-specific data is not available, parameters can be estimated from the literature. Table 1 from Duncan (2000) provides ranges for the coefficient of variation, *COV*, for various soil properties commonly used in slope stability computations. The *COV* is the ratio between the standard deviation and the mean. Table 1 also provides *COV* values for insitu testing parameters.

Table 1 - Ranges of COV from Duncan (2000)

Property	Coefficient of Variation, *COV* (%)
Unit Weight, γ	3 - 7
Effective Friction Angle, ϕ'	2 - 13
Undrained Shear Strength, S_u	13 - 40
Undrained Shear Strength Ratio, S_u/σ_v'	5 - 15
Standard Penetration Test Blowcount, N	15 - 45
Electric Cone Penetration Test, q_c	5 - 15
Mechanical Cone Penetration Test, q_c	15 - 37

In a reliability analysis, satisfactory performance (e.g., safety) for a specific limit state is expressed in terms of a performance or limit state function, $G(\underline{x})$. The performance function is formulated such that 'failure' corresponds to values of $G(\underline{x}) < 0$ and 'safety' corresponds to values of $G(\underline{x}) > 0$. In the context of slope stability $G(\underline{x}) = F_s - 1$, where F_s is the factor of safety against slope failure as computed by a particular method. Therefore, $G(\underline{x})$ is a function of all relevant material, geometric and load variables for a slope stability analysis. Thus, the reliability index is minimized by allowing Microsoft Excel to change variables used in the slope stability computation under user-defined constraints such that the performance function equals zero. Similar procedures are employed for analyzing the lateral spreading case histories.

Flow Liquefaction and Lateral Spreading Case Histories

The historical failures to be analyzed as part of this project include both cases of flow failure and lateral spreading. Olson and Stark (2002) present a database of 33 case histories where liquefaction has been deemed the cause of failure; these are predominately cases of flow liquefaction. Table 2 contains the name, year of failure, and apparent cause of failure for the Olson and Stark (2002) case histories. Mabey and Youd (1997) also present a database of failures where liquefaction of cohesionless soils is the evident cause of failure. The Mabey and Youd (1997) database contains more than 200 cases of lateral spreading, mostly from Japan and the United States. Table 3 lists cases involving either flow liquefaction or lateral spreading that have been evaluated as possible additions to the existing databases. For all the cases listed in Table 3, relevant geotechnical data, and pre- and post-liquefaction geometries are available and have been obtained from different sources of information. It is expected that the cases shown in Table 3 will add about 40 new data points. In addition to cases identified in Table 3, the possibility of including cases from three other recent earth quakes, the 1999 Chi-chi earthquake in central Taiwan (Hwang and Yang, 2001), the 2001 Nisqually earthquake in Washington (Bray et al. 2001), and the 2003 San Simeon earthquake (Holzer et al. 2004), is being investigated.

Compiling the existing databases and the additional case histories will result in an updated database containing more than 300 data points of both flow liquefaction and lateral spreading type failures. Using the reliability-based slope stability spreadsheets developed as part of this research project, the expanded databases are being analyzed to obtain a distribution of reliability indices for both the flow liquefaction and lateral spreading failures. These results will be statistically examined to determine how much the yield and liquefied shear strengths differ between the flow liquefaction and lateral spreading cases. The results should also aide in determining whether or not the shear strengths should be normalized by the initial vertical effective stress.

Spencer's Spreadsheet

The Spencer's slope stability spreadsheet developed for this project uses the same spreadsheet procedures as presented by Low (2003) to perform stability computations. The reliability computations in the spreadsheet follow the Low and Tang (2004) approach as described previously. The Spencer's spreadsheet by Low (2003) is suitable for an embankment atop a soft foundation, however most flow liquefaction case histories have complicated geometries. Procedures were developed using built-in Microsoft Excel spreadsheet functions and Microsoft Visual Basic to overcome this drawback. The code enables the spreadsheet to determine correct material properties based on a pair of Cartesian coordinates within a given complicated cross-section. This technique should prove to be useful for all other stability spreadsheets created during the remainder of this research project

Table 2 - Case histories as presented by Olson and Stark (2002)

Case History #	Case History Name	Year of Failure	Apparent Cause of Failure
1	Vlietepolder	1889	High tide
2	North Dike of Wachusett Dam	1907	Reservoir filling
3	Calaveras Dam	1918	Construction
4	Sheffield Dam	1925	Santa Barbara EQ
5	Helsinki Harbor	1936	Construction
6	Fort Peck Dam	1938	Construction
7	Solfatara Canal Dike	1940	Imperial Valley EQ
8	Lake Merced Bank	1957	San Francisco EQ
9	Kawagishi-Cho Building	1964	Niigata EQ
10	Uetsu Railway Embankment	1964	Niigata EQ
11	El Cobre Tailings Dam	1965	Chilean EQ
12	Hokkaido Tailings Dam	1968	Tokachi-Oki EQ
13	Koda Numa Embankment	1968	Tokachi-Oki EQ
14	Metoki Roadway Embankment	1968	Tokachi-Oki EQ
15	Lower San Fernando Dam	1971	San Fernando EQ
16	Tar Island Dyke	1974	Construction
17	Mochi-Koshi Tailings Dam 1	1978	Izu-Oshima-Kinkai EQ
18	Mochi-Koshi Tailings Dam 2	1978	Izu-Oshima-Kinkai EQ
19	Nerlerk Embankment - slide 1	1983	Construction
20	Nerlerk Embankment - slide 2	1983	Construction
21	Nerlerk Embankment - slide 3	1983	Construction
22	Hachiro-Gata Road Embankment	1983	Nihon-Kai-Chubu EQ
23	Asele Road Embankment	1983	Pavement repairs
24	La Marquesa Dam - Downstream	1985	Chilean EQ
25	La Marquesa Dam - Upstream	1985	Chilean EQ
26	La Palma Dam	1985	Chilean EQ
27	Fraser River Delta	1985	Gas desaturation and low tide
28	Lake Ackerman Embankment	1987	Seismic reflection survey
29	Chonan Middle School	1987	Chiba-Toho-Oki EQ
30	Nalband Railway Embankment	1988	Armenian EQ
31	Soviet Tajik - May 1 slide	1989	Tajik, Soviet Union EQ
32	Shibecha-Cho Embankment	1993	Kushiro-Oki EQ
33	Higashiarekinai Route 272	1993	Kushiro-Oki EQ

Figure 1 shows a simplified flow chart illustrating how the program determines what material a particular point occupies and what properties correspond to that location. The user inputs a list a points and coordinate pairs defining all vertices of a given cross-section. The user then defines a series of boundary lines which are composed of the previously defined points. The piezometric surface is also defined with the original points. The various materials of the cross-section are then created by assigning a top and bottom boundary line which envelope that particular material. The boundary lines are defined so that all materials in the cross-section are easily identifiable with two of the defined lines. With this data, tables setup within the spreadsheet check whether or not a specific point is in each of the different materials and returns the material number in which the point resides. The material properties and probabilistic parameters corresponding to the specific point are then returned for further stability computations. If user defined constraints are satisfied, the solution is returned. However, if the constraints are not satisfied the slip surface is automatically changed until a solution is achieved. The procedure is implemented such that the material properties and probabilistic parameters are updated each time a different failure surface is evaluated.

Table 3 - Additional cases of flow liquefaction and lateral spreading to enlarge existing databases

Cause of Failure	Type of Failure	Approximate Number of Additional Points	References
1983 Nihonkai-Chubu EQ	Liquefaction at Port facilities	4	Noda et al. (1984)
1989 Loma Prieta EQ	Liquefaction at Moss Landing	3	Boulanger et al. (1997)
1990 Luzon (Philippine) EQ	Tilting and subsidence of buildings due to liquefaction, Dagupan	4	Tokimatsu et al. (1994); Acacio et al. (2001)
	Massive movements along river banks, Dagupan	3	Ishihara et al. (1991); Ishihara et al. (1993)
1994 Northridge EQ	Liquefaction and pipeline failures along Balboa Blvd.	2	Holzer et al. (1999)
1995 Kobe (Hyogoken-Nambu) EQ	Lateral displacements behind quay walls, Port Island and Rokko Island	5	Ishihara et al. (1996); Inagaki et al. (1996); Shibata et al. (1996); Ishihara (2002)
	Embankment failures, Niteko reservoir	3	Towhata et al. (1996)
	Damage to river dikes	3	Matsuo (1996); Ozutsumi et al. (2002)
	Damage to building foundations	>3	Tokimatsu et al. (1996)
	Takarazuka landslide	1	Sassa et al. (1996)
1999 Kocaeli (Izmit), Turkey, EQ	Large ground displacements, Sapanca lake	2	Cetin et al. (2002)
	Tilting and Subsidence of buildings, Adapazari	>3	Sancio et al. (2002); Mollamamutoglu et al. (2003)

Fort Peck Dam Flow Liquefaction Failure

Preliminary results from the yield strength reliability-based back analysis of the 1934 Fort Peck Dam flow liquefaction failure are subsequently presented. Figure 2 shows an aerial photograph of the Fort Peck Dam shortly after the failure occurred. As reported by Olson (2001), this particular failure appears to be a result of excessive movements within the embankment induced during construction causing liquefaction within the hydraulically placed upstream shell. Table 4 shows material properties and probabilistic parameters for the various materials comprising Fort Peck Dam. The data contained within Table 4 are based on values used by Olson (2001). The material properties shown in Table 4 are assumed to follow the normal probability distribution. Based on the recommended ranges of *COV* provided by Duncan (2000), a *COV* of 20% is assumed for the undrained shear strength of the liquefiable zone while a *COV* of 10% is assumed for all other material properties.

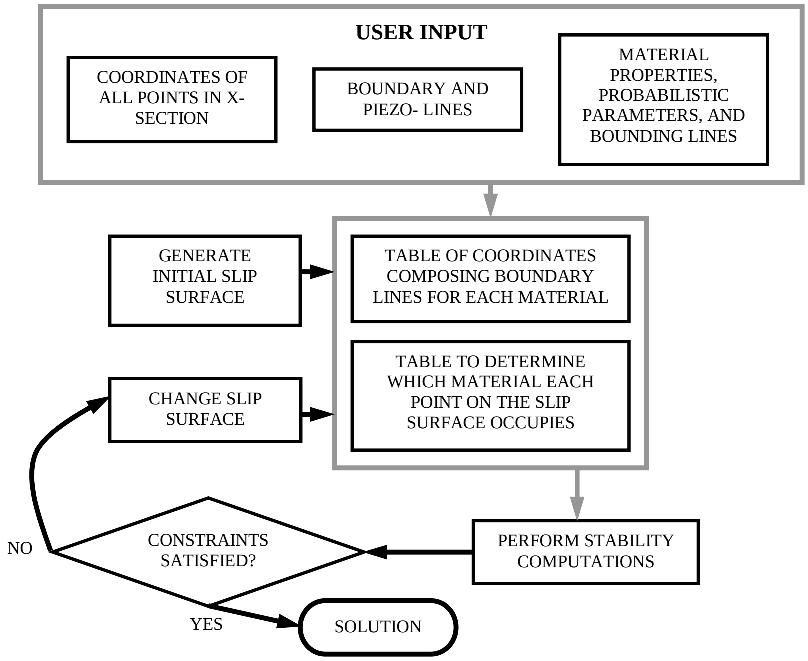

Figure 1 - Flowchart illustrating how the spreadsheet determines which material each point along the failure surface occupies

Figure 3 shows the cross-section of Fort Peck Dam roughly corresponding to the pre-failure geometry (Olson, 2001); all materials presented in Table 4 are defined in Figure 3. The circular failure surface shown in Figure 3 corresponds to the minimum reliability index for the back analyzed yield strength. For these preliminary analyses it is assumed that the different material properties within the cross-section are uncorrelated. The analysis indicates that the yield shear strength of the liquefiable shell is 93.7 kPa with a reliability index of 0.70. Assuming that the reliability index follows a normal distribution, the probability of failure for the pre-failure geometry of Fort Peck Dam is computed as 24.2%; an obviously unacceptable value.

REPORTS PUBLISHED

As to date no reports have been published regarding the results of this ongoing research project; however several documents including an MS thesis dissertation is currently in draft.

DATA AVAILABLITY

All processed data are available from the author's in hardcopy and electronic formats. Excel programs, when completed, will also be available from the author's. Dr. Marte S. Gutierrez can be reached via email at magutier@vt.edu or by telephone at (540) 231-6357. Mr. Morgan A. Eddy can be reached via email at meddy@vt.edu or by telephone at (540) 231-4417.

Figure 2 - Aerial photo of Fort Peck Dam following the 1934 failure from Olson (2001)

Table 4 - Material parameters used in analysis of Fort Peck Dam

Material	γ_m	γ_{sat}	ϕ'	c'	S_u
	kN/m^3		deg.	kPa	kPa
Alluvium	19.00	20.00	40.00	0.00	-
Core	18.00	19.00	30.00	0.00	-
Liquefiable Shell	18.20	19.20	-	-	82.90
Non-Liquefiable Shell	18.20	19.20	30.00	0.00	-
Reservoir	9.81	9.81	0.00	0.00	0.00

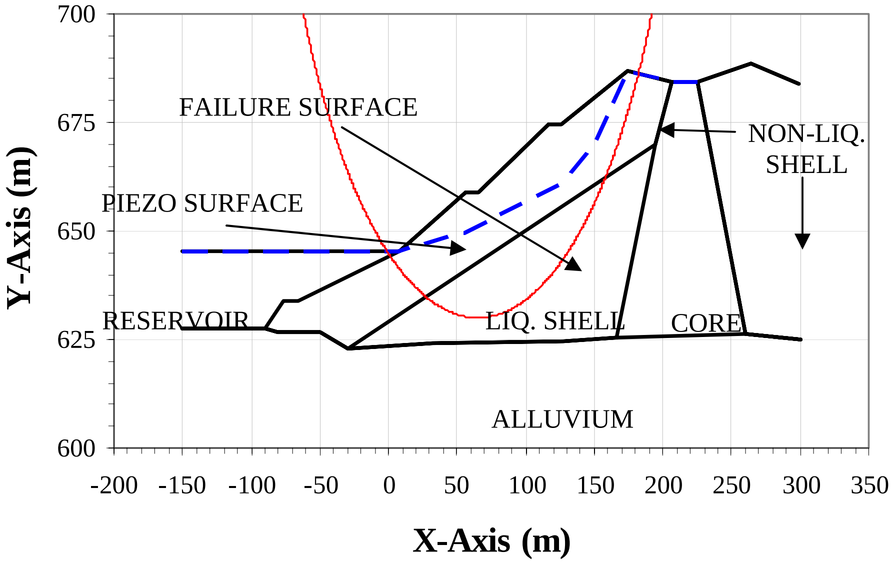

Figure 3 - Pre-failure cross-section of Fort Peck Dam used for reliability-based back analysis, illustrating the various zones within the dam as well as the piezometric and failure surfaces.

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